

THE SNS RING DIPOLE MAGNETIC FIELD QUALITY*

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Abstract

The large acceptance and compact size of the Spallation Neutron Source (SNS) ring implies the use of short, large aperture dipole magnets, with significant end field errors. The SNS will contain 32 such dipoles. We report magnetic field measurements of the first 16 magnets. The end field errors have been successfully compensated by the use of iron bumps. For 1.0 GeV protons, the magnets have been shimmed to meet the 0.01% specification for rms variation of the integral field. At 1.3 GeV, the rms variation is 0.036%. The load on the corrector system at 1.3 GeV will be reduced by the use of sorting.

1 INTRODUCTION

The Spallation Neutron Source (SNS) is under construction at Oak Ridge National Laboratory [1]. The SNS accumulator ring [2] will contain 32 sector dipoles. To accommodate the high intensity proton beam, the magnet aperture is large. The dipoles are being characterized over the energy range 0.8 to 1.3 GeV to allow for operation over a range of injection energies. The magnets were fabricated at Brookhaven National Laboratory (BNL), using coils and machined iron parts purchased from industry. The yokes are machined from solid 1006 steel. Other parameters of the magnets are given in Table 1. A drawing of the magnet is shown in Fig. 1. This paper reports magnetic measurement results from the first 16 dipoles.

Table 1: Magnet Parameters

Effective length, m	1.44
Gap, mm	170
Pole width, mm	450
B_0 at 1.0 GeV (1.3 GeV), T	0.77 (0.925)
I_{op} at 1.0 GeV (1.3 GeV), A	4398 (5408)
$\int B \cdot dl$ at 1.0 GeV (1.3 GeV), T-m	1.11 (1.33)

2 FIELD QUALITY REQUIREMENTS

For the individual magnets, there are field quality requirements for the integral field and for the region near the axial center of the magnet, where the field is two-dimensional. (The requirement applies to the integral field after the linear variation of the integral dipole field with horizontal position due to the sector ends is subtracted.) In both cases, the requirements call for

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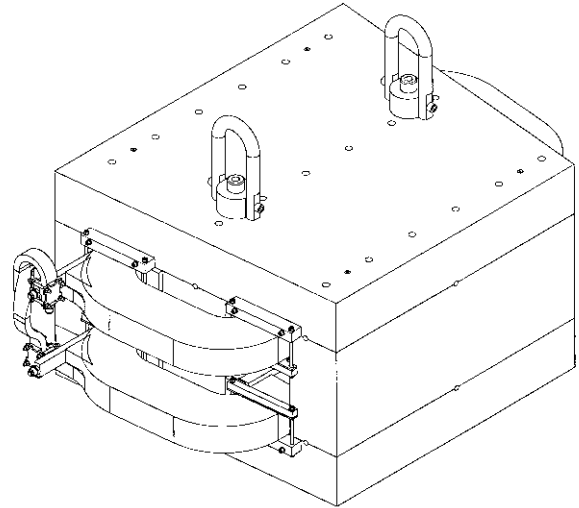


Figure 1: SNS Ring Dipole

0.01% uniformity across an aperture of ± 100 mm at the horizontal midplane. Field uniformity near the axial center of the magnet was achieved by locating steel strips 5.19 mm high and 40 mm wide at the edges of the poles. Uniformity of the integral field was achieved by adjusting the amount of steel at the corners of a yoke of the prototype dipole in an iterative process that utilized both three-dimensional calculations and measurement.

For the group of magnets, the rms variation of the integral field is to be less than 0.01%. After measurement, the magnets are disassembled in order to install the vacuum chamber, so magnet assembly must be reproducible to 0.01% in order to assure that the field measurements correctly represent the installed magnets. The six yoke sections (poles, top and bottom plates, side plates) are pinned and bolted to obtain this reproducibility.

3 MAGNETIC FIELD MEASUREMENTS

The integral fields in production dipoles are measured with a rotating coil 2.49 m long and 163.8 mm in diameter. Tangential sense windings are mounted on the coil [3]. At 1.0 and 1.3 GeV, measurements are made at the center of the magnet aperture and at positions 50.8 and 101.6 mm on both sides of center. The regions covered by the coil at these positions overlap, providing considerable redundancy in the data. For a sector magnet, accurate horizontal placement of the measuring coil is essential. (A horizontal displacement of 0.76 mm changes the integral field by 0.01%.) This is accomplished by a precision magnet stand and a computer controlled coil translation stage. In addition, optical survey is used to locate fiducials on the coil with respect to the magnet fiducials. The survey data are then used to correct the magnetic measurements for any errors in the coil position.

The short-term variation (i.e., noise) of the integral measurements is $\sim 0.002\%$. The reproducibility of the measurements is $\sim 0.01\%$ when the magnets are removed from and reinstalled on the test stand. The absolute accuracy of the integral field measurement is estimated to be $\sim 0.03\%$.

It was found that a single cycle of the magnet to high current and back is sufficient to obtain reproducibility of the hysteresis. (For 1.0 GeV measurements, the magnets are ramped to 4834 A, about 10% above the operating point of 4398 A. For 1.3 GeV measurements at 5408 A, the magnets are ramped to the maximum current available at the test stand, 5450 A.) Following the cycle, the magnet is ramped up to the same high current. Measurements are then made on the down-ramp. After ramping down to a new current, a wait time of 2 minutes is imposed to let eddy currents die away. The magnet current is measured with two DCCTs in series. It was verified that the measurements were independent of the polarity of the current.

Measurements of the magnets after their initial assembly showed an integral field variation much larger than the 0.01% tolerance. The largest variation was $\sim 0.25\%$ from the mean. Only about 1/3 of this variation could be explained by the magnet-to-magnet variation in the pole gap. After ruling out various possible measurement errors, the remaining variation was attributed to differences in the properties of the iron yoke. (Production of the yoke material required 7 pours.)

The magnets have been brought into tolerance at 1.0 GeV by adding shims under the lower pole or under the vertical flux return sections of the yoke to decrease or increase the gap, respectively. In these locations, the shims are not disturbed when the top plate is removed to install the vacuum chamber. The shim material, 1010 steel, is available in increments of 25 μm . A 25 μm change in gap changes the integral at 1.0 GeV by 0.014%. This is consistent with the fractional change in gap height within $\sim 7\%$. The slight difference may be a result of using the 1010 steel shim. Integral field measurements of the first 16 magnets, at the central position, before and after shimming, are shown in Fig. 2. Before shimming,

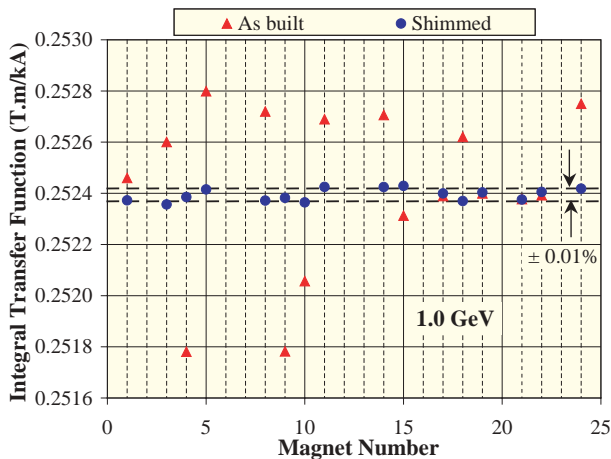


Figure 2: Integral dipole field at 1.0 GeV before (triangles) and after (circles) shimming.

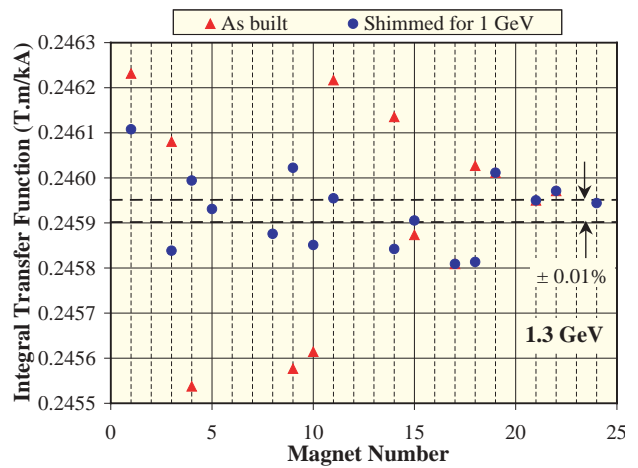


Figure 3: Integral dipole field at 1.3 GeV before (triangles) and after (circles) shimming.

the rms variation of the integral field was 0.127%; after shimming, it is 0.01%. At 1.3 GeV, shimming reduced the rms variation from 0.095% to 0.034% (Fig. 3). Local dipole correctors will be used to correct the orbits. To minimize the load on these correctors, the dipoles will be sorted based on their integral field at 1.3 GeV. Magnets with high and low integral fields will be placed 360 degrees in phase advance (two full cells) apart.

With the measuring coil at the central position, excitation curves for operation at 1.0 and 1.3 GeV are measured, down to 0.8 GeV. Fig. 4 shows the excitation curves in the two cases.

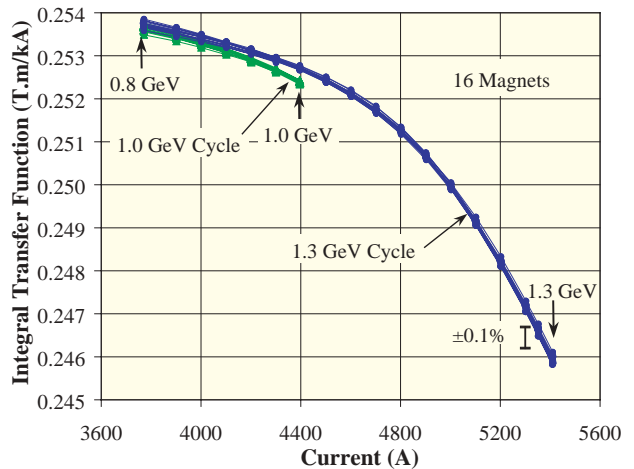


Figure 4: Excitation curves for operation at 1.0 GeV and 1.3 GeV

An alternate way to represent the field quality of the magnets is to give the harmonic decomposition of the field. Table 2 gives the harmonics of magnet SD1701 in the two-dimensional region of the magnet, as measured by a rotating coil 0.92 m long and 136.8 mm in diameter. The harmonics are given at a reference radius of 80 mm in “units,” which are 10^{-4} of the fundamental field. No harmonic is larger than 1 unit. Similar results are obtained for the integral harmonics in all magnets. As an example, Table 3 shows the integral harmonics in the

Table 2: 2-D harmonics in the dipole SD1701

Harmonic	Value in "units" at 80 mm	
	Normal	Skew
Dipole	10000	0.00
Quadrupole	-0.09	0.89
Sextupole	0.02	-0.08
Octupole	0.05	0.02
Decapole	0.46	0.05
Dodecapole	-0.19	0.02
14-pole	-0.07	-0.04
16-pole	0.21	-0.03
18-pole	0.16	0.06
20-pole	-0.22	0.09
22-pole	-0.32	-0.06

Table 3: Integral harmonics in the dipole SD1711

Harmonic	Value in "units" at 80 mm	
	Normal	Skew
Dipole	10000.0	0.00
Quadrupole	-105.21	0.10
Sextupole	0.56	-0.50
Octupole	2.06	0.01
Decapole	0.97	-0.04
Dodecapole	0.18	-0.06
14-pole	-0.28	0.04
16-pole	0.05	0.05
18-pole	-0.06	-0.02
20-pole	0.01	-0.04
22-pole	-0.22	0.01

magnet SD1711 at the central position of the measuring coil. It is important to note that the integral measurements of two harmonics are affected by the magnet taper, which produces an apparent normal quadrupole of -105 units ($\sim 1\%$) and an apparent normal octupole of ~ 2 units. A three-dimensional calculation shows that the apparent values of these harmonics are -107 and $+1.96$ units respectively, in reasonable agreement with the measured values. The harmonics are essentially unchanged by the shimming. Both 2-D and 3-D calculations were performed to show that changes in harmonics due to the shims are negligible. Typical harmonic changes in the magnets measured so far are less than 0.1 unit.

The three-dimensional calculation also allows us to evaluate the difference between the harmonics measured by the (straight) integral coil and those along the curved path of a proton. Except for the normal quadrupole and normal octupole as discussed above, the harmonics integrated along the trajectory of the protons are expected to be within 1 unit of those measured by the rotating coil. The integral normal quadrupole and the normal octupole for the curved path differ from the straight path value by 99.4 units and 2.7 units respectively.

4 CONCLUSIONS

The first 16 ring dipoles for the Spallation Neutron Source have been measured and found to meet the field quality tolerances. The 2D fields are uniform across the good field region of $x = \pm 100$ mm within 0.01%. Except for a residual quadrupole, estimated at ~ 6 units due to the magnet taper, the same is true of the integral field. When shimmed, the magnets meet the 0.01% tolerance on the rms variation of integral dipole field at 1.0 GeV. The rms variation at 1.3 GeV, 0.036%, will be compensated by sorting.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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